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An Experimental Ringbom-Stirling Engine

Summary Report

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AN EXPERIMENTAL RINGBOM-STIRLING ENGINE

by

G. Walker and O.R. Fauvel
Department of Mechanical Engineering
University of Calgary
Calgary, Alberta

for the
Transportation Development Centre
Transport Canada

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G. Walker and O.R. Fauvel

Department of Mechanical Engineering

University of Calgary

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Transport Canada

Montreal

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17. Abstract

A proof of-principle Ringbom-Stirling engine built using parts from a commercially available diesel engine has been demonstrated. The engine used air as the working fluid and water as the lubricant. It was developed as part of a wider study concerned with large coal-burning Stirling engines for use in railway locomotives, ships, off-highway vehicles for mining, construction, agriculture, forestry and for stationary power.

Conversion of diesel engines to Ringbom-Stirling engines offers the prospect of gradual conversion to coal-burning operation rather than direct replacement by new equipment.

The experimental engine was not tested under the design conditions of speed and pressure because of safety concerns. The results achieved at low pressures and speeds indicate that design output would probably be achieved at the design conditions.

A computer simulation program developed during the work was used to perform parametric studies of the effects of change in the principal design parameters. This study revealed the significance of the mass of the displacer in the proper operation of a Ringbom engine including speed control. An important consequence was the concept for a new type of Ringbom-Stirling engine with independent displacer drive.

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17. Résumé

Un moteur Ringbom-Stirling devant servir à démontrer le principe en jeu, et réalisé en modifiant un moteur diesel de fabrication courante, a été essayé; il a utilisé l'air comme fluide de travail et l'eau comme lubrifiant. Sa réalisation fait partie d'une étude s'intéressant aux gros moteurs à cycle de Stirling chauffés au charbon et destinés à la propulsion de locomotives, de navires, de véhicules hors routes, ainsi qu'à la production d'énergie et à diverses autres applications minières, agricoles, forestières, etc.

Le cycle Ringbom-Stirling ouvre la perspective d'une conversion graduelle des moteurs actuels à combustion interne en moteurs à combustion externe brûlant du charbon, évitant ainsi leur remplacement intégral.

Ce moteur expérimental n'a pas été essayé dans les conditions normales de vitesses et de pressions, pour des raisons de sécurité. Mais les résultats ont montré que le rendement attendu aurait pu être atteint si les vitesses et les pressions mises en oeuvre avaient été normales, au lieu d'être réduites comme cela fut le cas.

Un programme de simulation assistée par ordinateur, mis au point en cours de route, a été utilisé pour vérifier l'effet des variations dans les paramètres de base. C'est ainsi qu'a été mise en évidence l'importance de la masse du déplaceur dans le rendement d'un moteur à vitesse variable. Ces travaux ont débouché sur un modèle nouveau de moteur Ringbom-Stirling disposant d'un entraînement séparé pour le déplaceur.

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Moteur à cycle de Stirling. Moteur Ringbom de traction ferroviaire. Charbon.	Le CDT dispose d'un nombre limité d'exemplaires.

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1.0 INTRODUCTION

A Stirling engine is a heat engine absorbing heat at high temperature from some external source, converting some to work, and rejecting the balance as waste heat near ambient temperatures.

High temperature heat is supplied to the engine from an external source, and can be of any origin, combustion of solid and liquid fuels, concentrated solar energy, or radioisotope heat. In this regard Stirling engines are similar to Rankine cycle engines (steam engines). Both are candidates for coal-burning engines as alternatives to oil-burning diesel engines.

The principal difference between Rankine and Stirling engines is in the thermodynamics of the cycles. The Rankine cycle involves the evaporation and condensation of the working fluid and so the maximum and minimum temperatures of the cycle are inimicably related to the maximum and minimum pressures in a way characteristic of the working fluid. The result is an ensemble of machinery, boiler, condenser, reciprocating engine or expansion turbine and auxiliaries that is large, heavy but with a high thermodynamic efficiency, i.e. 40%. Systems which operate without a condenser are smaller and lighter but have a low thermodynamic efficiency, i.e. 10%.

A Stirling engine uses a gaseous working fluid and therefore the pressure and temperature levels may be independently chosen. Moreover, the thermodynamic cycle incorporates a regenerative heat exchanger which 'recycles' a substantial fraction of the energy flowing through the system. As a consequence the Stirling engine has the potential to be a coal-burning unit of moderate size and weight and with a reasonable thermodynamic efficiency, i.e. 30/35%.

Both Stirling and Rankine engines can operate on liquid fuels but neither offer any economic or performance advantage over internal-combustion engines; so long as diesel oil is available, the best engine for its use is the diesel engine. Nevertheless, it is prudent to recognise that coal is the world's most abundant fossil fuel and to consider, for future application, the alternatives to oil-burning engines.

In this spirit of enquiry Walker (1981a)* examined the possibilities of the Stirling engine for railway locomotive application with particular regard to the Canadian environment. This report is an important reference document to the topic of interest here and was well summarized by Walker *et al* (1982).

In the locomotive application study the proposal was made for

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*References given in full at the end of the text.

novel Ringbom-Stirling engines using air as the working fluid and water as the lubricant. It was further proposed that such engines could be made by converting existing diesel locomotive engines using many of the same parts and components and that savings could therefore result from the gradual conversion of existing diesel-powered locomotive fleets to coal-burning operation, rather than the outright replacement required for steam locomotives. The modified diesel engine working as a Ringbom-Stirling unit would operate in combination with a fluidised bed coal combustor and a sodium heat pipe thermal transport system.

The report further recommended the concept be investigated, by a proof-of-principle demonstration Ringbom-Stirling engine converted from an industrial diesel engine. That investigation is the substance of the report presented herein.

The essential elements of a Stirling engine include two spaces, at different temperatures, whose volumes can be varied cyclically but out of phase by approximately 90°. In a power system the hot space is called the expansion space and the cold volume is the compression space. The two spaces are coupled through three heat exchangers, the heater, regenerator and cooler.

A Ringbom-Stirling engine is a special form of Stirling engine characterized by a free displacer and a piston coupled by a connecting rod to the engine crankshaft. The displacer moves in the displacer cylinder entirely under the action of pressure forces upon it. The specialist technology of free-piston engines has been summarized by Walker *et al* (1985).

Engines of this type were invented at the University of Calgary in 1970 (see Walker (1973)) and were called 'Hybrid-Stirling engines'. The principal attraction was the potential offered to convert internal combustion engines to Stirling operation. Later the original 1907 patent of Ossian Ringbom became known and Stirling engines with free displacers were then called Ringbom-Stirling engines.

Little previous work on Ringbom-Stirling engines has been reported in the literature but a 1 horsepower prototype unit was developed in 1980/81 by Sunpower Inc., Athens, Ohio in a program sponsored by a major United States engine builder. Sunpower Inc. is a research/development company specialising in free-piston Stirling engine systems. The 1 horsepower prototype engine operated successfully but was considered by the sponsor to be uneconomic for commercial production. For this reason the prototype development was not continued beyond the initial stage.

A participant in this pioneer Sunpower development, Dr. J. Senft, now a professor at the University of Wisconsin, was engaged as a consultant for the Transportation Development Centre/University of Calgary Ringbom-Stirling engine project. His report, Senft (1981a), and subsequent publications (Senft (1981b), Senft (1983)) are the pioneering contributions to the theory of Ringbom-Stirling engines.

Following a careful evaluation of commercial diesel engines the Lister 8/1 single-cylinder slow speed diesel engine was selected for conversion. An engine of this type was obtained and the engineering design for the conversion was carried out. Complete details of the design study were presented in a design report (Walker (1981b)).

Construction of a Ringbom-Stirling engine using parts of the Lister engine and the creation of an engine test bed with the associated instrumentation was carried out at the University of Calgary and the unit was installed in temporary facilities. Engine development and testing commenced shortly thereafter.

Considerable developmental work was carried out to bring the engine to an operating condition. Following this some 20 hours of actual test time was accomplished on a schedule of increasing pressure and speed. The maximum power achieved was a net engine output of 1.85 KW at a mean pressure and speed of 2.5 MPa (371 lb per sq in) and 6.9 Hz (424 R.P.M.). Operation of the engine at higher pressures and speeds in reasonable safety was not possible in the temporary installation and it was decided to cease the further engine tests to raise the operating conditions and power output to the design point.

A prototype Ringbom-Stirling engine with bore and stroke characteristics identical to the Lister diesel engine employing air as the working fluid and water as the lubricant was built and operated to produce a surplus of power at the shaft. The further work necessary on the engine was thought to be largely of an engineering development nature best carried out in an establishment with adequate test facilities, primarily an engine test cell.

The objective of the further work required would be to increase the engine power output by increase in speed and pressure levels, to simplify and improve the engine control and combustion systems, to investigate alternative corrosion-resistant coatings and to optimise the water lubrication/seal/bearings system from the aspect of design and operation.

The project is regarded as successful overall despite the limitation on speed and pressure levels due to safety considerations. In course of the work the fundamental theory of Ringbom-Stirling engines was developed and verified experimentally, particularly with regard to displacer motion. A small model Ringbom-Stirling engine constructed independently of the project in conjunction with high speed photographs confirmed the actual motion of the displacer was virtually identical to that predicted for Ringbom-Stirling engines in the consultant's report by Dr. J. Senft.

A sophisticated computer simulation program for Ringbom-Stirling engines was developed in course of the project and was used to establish a rational basis for the design of Ringbom-Stirling engines.

Finally, several original design concepts for major components of Stirling engines emerged during the project and will be incorporated in future engine developments.

For the period January to July 1983 the Principal Investigator was on leave from the University of Calgary to study the technology of sodium heat pipes and their application to Stirling engines. A report (Walker (1983)) summarizes the findings. Although not part of the work reported here it is an important reference directly relevant to the combination of a Stirling engine system with a fluidized bed coal combustor.

In summary, at this juncture the experimental engine has not been subjected to sufficient testing to establish its potential operation performance. Continuation of testing at design pressures and speeds has been postponed until the U of C acquires adequate test facilities or TDC decides to resume development and testing elsewhere.

2.0 ENGINE DESIGN

2.1 General

The mechanical design of the prototype engine was carried out as the initial task of the project well ahead of the development of a computer simulation program. The design was accomplished using the best available methods to fulfill an engine specification arbitrarily selected.

General arrangement and detail component drawings for the complete engine system and the test bed installation were prepared and submitted to TDC for approval. The original engineering drawings are on file in the Department of Mechanical Engineering, University of Calgary.

The design report (Walker (1981b)) contains a full account of the detailed design considerations and associated work.

The Lister 8-1 engine shown in Figure 1 was used to provide the crank, crank case and flywheel of the experimental engine. The Lister cylinder was used as a crosshead guide. The Lister engine is rated at 5.9 KW (eight horsepower) with a bore of 114.3 mm (4.5 ins) and a stroke of 133.35 mm (5.25 ins) running at 13.33 Hz (800 revolutions per minute). The engine is conservatively rated, of vintage design and principally used for agricultural purposes as a small stationary power plant. It was well-suited for this project typifying in many respects railway diesel engine technology, i.e. slow running, conservative rating. Many parts were removed (cylinder head, fuel pump, etc.) and substantial mass was added to the twin flywheel.

The engine was completely disassembled and all the internal surfaces plated with poly-tetra-fluoro-ethylene, as a protection against corrosion by the water lubricant. The journal surfaces of the crankshaft were also chrome-plated for corrosion protection.

The experimental Ringbom-Stirling engine is shown in cross-section by Figure 2. The piston of the diesel engine was replaced with a crosshead and was coupled by a piston rod to the power piston of the Stirling engine. The space *above* the power piston was the 'compression space' of the Stirling engine.

This space was in communication with a second cylinder containing the displacer, a hollow vessel consisting of a stainless steel dome on a stainless steel base.

The displacer cylinder comprised an array of parts consisting of a water cooled 'cooler' at the bottom and a thick wall stainless steel 'heater' at the top. A close packed wire 'regenerator' was sandwiched between.

The space above the displacer was the 'expansion space'. The space below the displacer was part of the compression space in direct communication with the compression space above the piston.

The expansion space was connected to the dual compression spaces through internal flow passages in the cooler, void spaces in the regenerator and an ensemble of heater tubes shown in Figure 2.

A displacer rod of relatively large diameter was attached to the displacer with a spring piston fitted to it at the lower end. The piston operated in a spring cylinder. Gas springs of variable volume were provided above and below the spring piston.

The displacer is a low mass structure caused to move in the displacer cylinder by the difference in pressure between the expansion space and the spring cylinder acting over the area of the displacer rod. The gas springs serve to decelerate the piston at the end of each stroke and to help reverse the direction of motion of the displacer.

The heater head was enclosed in a thermally insulated dome equipped with inlet and exit ports. Hot combustion gases produced by the combustion of propane and oxygen entered through the inlet port, heated the heater tubes and then exited the dome. The gases were burned in two standard commercial heating torches in a combustion chamber immediately upstream of the heater dome.

The space below the power piston is called on Figure 2 the 'buffer space'. This was pressurized to the mean cycle pressure in the working space so as to relieve the load on the running gear of the engine. Pressurization of the buffer space to $\bar{p}$ (the mean cycle pressure) reduces the pressure difference across the piston to $(p_{ins}-\bar{p})$ rather than $(p_{ins}-p_{at})$ with an unpressurized buffer space. p_{ins} is the instantaneous pressure in the engine working space, p_{at} is the atmospheric pressure.

In the fully developed double-acting reservoir of the engine the buffer space would become a second compression space acting in concert with another displacer cylinder to form a second Stirling engine system. On grounds of economy and to expedite the project the second Stirling engine system was never incorporated in the prototype engine.

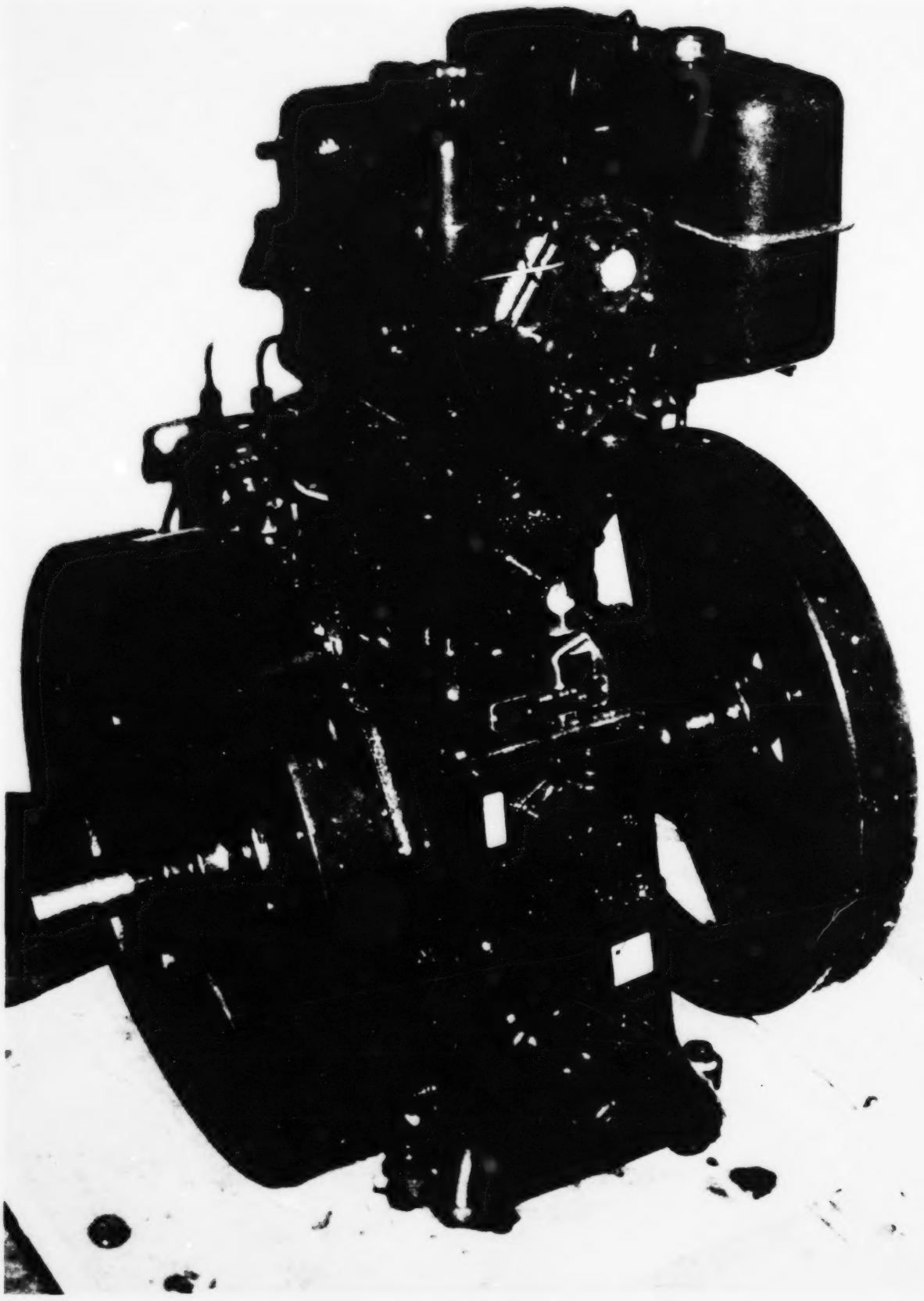

Figure 1 Lister Model 8/1 Diesel Engine

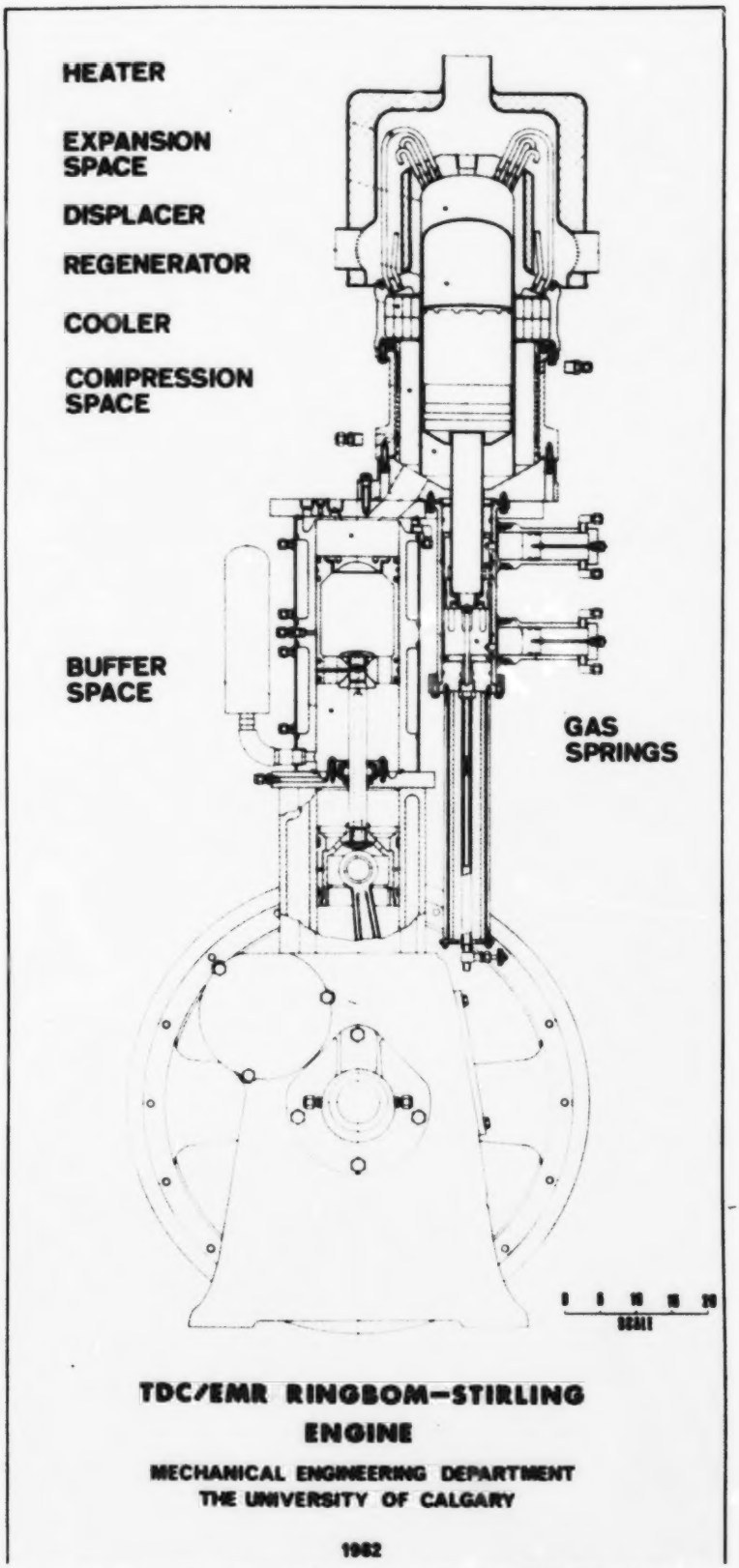

Figure 2 Cross-Section of the TDC Ringbom-Stirling Engine

3.0 PRE-TEST TRIALS

3.1 General

On completion of fabrication and assembly of the components comprising the Ringbom-Stirling engine a number of hours of engine operation were used to acquire experience in the running of the engine, to remedy operational and performance problems, and to gain some early indications of the performance of the engine.

Over the period during which the trials were conducted, changes in several components were implemented including the gas spring assembly, the displacer, the displacer cylinder base, and the power cylinder. These changes allowed the power output from the engine to be increased by gradually raising the heating temperature, mean working space pressure, and RPM.

Operation of the engine system requires diligent monitoring of all systems by an operator who is thoroughly acquainted with the configuration and function of all parts of the engine. Additional manpower is required for the operation of the recording equipment and also for maintenance of a safety surveillance.

3.2 Operating Data

Over the testing period results were obtained which may be described as either, a) quantitative, or b) qualitative, as outlined below. Progress of the trials may be traced by listing them along with values of key operating variables but preceded by description of the typical output from each test. A summary of the principal results achieved is given in Table 1.

Both the hardware and software were continuously upgraded during the trials so that meaningful comparisons between one test result and another are not possible.

Key parameters are presented in Table 1 for each of the engine tests listed. In addition, the summary indicates the additional records maintained. Chart recordings of piston and displacer positions and working space and/or gas spring pressures were obtained for many tests although only two simultaneous records could be obtained at any time.

The output of the MACSYM computer used was developed over the testing period to obtain a suitable compromise between the amount of information presented and the time available for output.

3.3 Analysis of Operating Data

To achieve displacer motion approaching that of the prediction models it is necessary to ensure the pressure variation of the gas spring associated with the displaced volume of the displacer rod is

reduced to a tolerable level.

Design and construction of the displacer is critical. The hollow vessel must be pressured to prevent collapse and free motion is required to achieve proper running. The displacer mass must be minimized in order to improve the engine power by allowing the engines to run at reasonably high speeds.

In the experimental engine friction in the running gear was very high. This was determined by measuring the shaft output power for a particular trial and comparing it with the indicated power determined from an engine P-V diagram. For Run 2 (28 March 1983) the brake power was 1.24 kW compared with an indicated power of 2.0 kW. Separate tests performed by motoring only the crankshaft also indicated values of friction coefficient much higher than expected.

It was found that during operation of the engine adjustment of the gas spring pressure was particularly important to achieve the desired displacer motion even when the engine speed and mean working space pressure were well matched.

The Beale equation indicates in the most general terms that the power output of a Stirling engine increases with operating pressure, speed, and temperature difference. If the operating temperatures for a particular engine were to remain constant, the power output should vary linearly with speed and linearly with pressure.

The Ringbom-Stirling engine is a special case since the phase angle between the piston and the displacer (or some equivalent factor since the displacer motion is typically not the same form as the piston motion) depends upon the relationship between speed and pressure. Parametric studies using the digital simulation program developed for this project indicated that, for a given pressure, the maximum engine power occurred at a specific speed.

With this in mind Figure 3, shown overleaf, was plotted to indicate the distribution of results obtained from tests which produced more than 0.10 kW. Had all tests been performed at the same temperature conditions it is expected that a gradual increase in power output as pressure and speed followed would have been obtained. The figure shows that this was not the case and rationalization of the results on the basis of correction for temperature variation does not improve the consistency of the results. It was concluded that a number of unknown variables influencing the engine performance were not under experimental control during the tests.

Future measures could include a more detailed and systematic examination of the operation of the engine. Areas of interest are:

a) Mechanical - the interaction of self-lubricating solids and water lubricant is not well understood. More direct experiments will reveal means by which design of this type of bearing may be substantially improved.

b) Fluid dynamics - the flow patterns within the engine are complicated. Problems to be addressed include examination of gas spring and balance space irreversibilities and means by which better flow passages may be designed and manufactured.

c) Optimum heat exchanger design remains a continuing focus of attention since designs are also subject to pressurization loadings and difficulties of manufacture as well as reduction of dead volumes.

d) Displacer motion control is clearly of prime importance. In the Ringbom-Stirling engine the basic problem is complicated by the variable speed capacity of the engine.

e) Engine control systems - the sensitivity of engine performance to the operating conditions and the dangers involved in straying from the design conditions both represent major areas of concern.

RESULT SUMMARY

Date	Run No.	Seq. No.	RPM	CSP	BSP	M	Torque[1]	kW[1]	Position Record Piston	Position Record Displacer	Pressure Record Wk'g. Sp.
20 Jan.	1	1	74	0	0	16	0.0	0.00	x	-	x
	2	2	113	0	0	15	-1.3	-0.02	x	-	x
	3	3	178	0	0	15	-1.4	-0.03	x	-	x
	4	4	301	0	0	16	-0.7	-0.03	x	-	x
	5	5	492	0	-1	16	0.0	0.00	x	-	x
	6	6	104	31	5	17	-7.3	-0.11	x	x	x
	7	7	188	33	6	17	-5.1	-0.13	x	x	x
	8	8	297	34	6	18	-4.4	-0.19	x	x	x
	9	9	494	35	7	18	-4.4	-0.31	x	-	x
	10	10	123	83	4	14	-46.1	-0.81	x	x	x
	11	11	182	83	5	12	-30.7	-0.79	x	x	x
	12	12	309	83	5	8	-24.9	-1.09	x	x	x
	13	13	492	86	5	1	-24.2	-1.69	x	x	x
	14	14	478	94	2	-17	-32.2	-2.19	x	x	-
21 Jan.	1	15	39	1	-1	17	-6.6	-0.04	x	-	x
	2	16	-	-	-	-	-	-	x	x	x
	3	17	174	35	29	19	-2.2	-0.05	x	x	x
	4	18	301	36	32	20	-1.5	-0.06	x	x	x
	5	19	490	39	38	20	-3.7	-0.25	x	x	x
	6	20	113	65	65	17	-12.4	-0.20	x	x	x
	7	21	178	64	67	16	-8.1	-0.20	x	x	x

es [1]) Negative values of torque and power indicate that the engine is being motored by the dynamometer.

Table 1: Summary of Experimental Results, Part I

RESULT SUMMARY (continued)

Date	Run No.	Seq. No.	RPM	CSP	BSP	M	Torque[1]	kW[1]	Position Record Piston	Position Record Displacer	Pressure Record Wk'g. Sp.
	8	22	293	64	69	13	-8.1	-.33	x	x	x
	9	23	492	67	74	8	-13.9	-.97	x	x	x
	10	24	156	247	256	8	-44.6	-.99	x	x	x
	11	25	320	253	281	5	-43.9	-3.00	x	x	x
	12	26	500	266	280	-3	-54.9	-3.90	x	x	x
2 Feb.	1	27	166	1	-1	16	0.7	.02	x	x	-
	2	28	254	1	-2	15	0.7	.02	x	x	-
	3	29	256	38	43	13	-5.1	-.19	x	x	-
	4	30	254	74	86	4	-13.0	-.48	x	x	-
	5	31	170	82	88	3	-15.0	-.37	x	x	-
	6	32	164	73	72	9	-11.0	-.26	x	x	-
	7	33	164	76	75	604	5.5	.13	x	x	-
4 Feb.	1	34	168	51	48	10	-8.5	.01	x	x	x
	2	35	162	55	48	534	1.5	.00	x	x	x
	3	36	168	55	48	608	3.8	.00	x	x	x
2 Mar.	1	37	160	124	129	6	-23	.00	-	-	-
	2	38	160	144	151	13	-28	-.01	-	-	-
	3	39	170	154	151	599	1.08	.00	-	-	-
28 Mar.	1	40	326	212	199	554	8.87	0.41	-	-	-
	2	41	438	360	340	588	20.0	1.24	x	x	-
29 Mar.	1	42	352	391	378	455	2.7	0.14	x	x	-
	2	43	410	326	313	568	12.4	0.72	x	x	-
	3	44	479	334	307	607	13.9	0.95	x	x	-
	4	45	514	390	336	605	10.0	0.73	x	x	-

Table 1: Summary of Experimental Results, Part II

RESULT SUMMARY (continued)

Date	Run No.	Seq. No.	RPM	CSP	BSP	M	Torque[1]	kW[1]	Position Record Piston	Position Record Displacer	Pressure Record Wk'g. Sp.
30 Mar.	1	46	480	367	336	-9	-7.4	-5.06	x	x	-
	2	47	516	181	181	545	3.4	0.25	x	x	-
	3	48	514	374	328	539	9.0	0.66	x	x	-
4 Apr.	1	49	430	217	186	-6	-37.5	-2.29	x	x	-
	2	50	365	271	264	571	18.8	0.97	x	x	-
	3	51	438	266	243	603	15.3	0.95	x	x	-
10 May	1	52	281	247	233	-7	-40.4	-1.61	x	x	-
	2	53	353	271	261	506	18.9	0.95	x	x	-
	3	54	471	345	315	522	16.5	1.10	x	x	-
	4	55	395	417	388	548	23.3	1.31	x	x	-
	5	56	553	490	396	491	2.1	0.17	x	x	-
	6	57	395	400	354	521	13.4	0.75	x	x	-
16 May	2	58	418	378	350	529	18.4	1.09	-	-	-
	1	59	412	353	313	547	16.0	0.94	x	x	x
17 May	1	60	410	332	309	610	23.9	1.39	-	-	-
	2	61	424	371	344	660	30.8	1.85	x	x	x

Table 1: Summary of Experimental Results, Part III

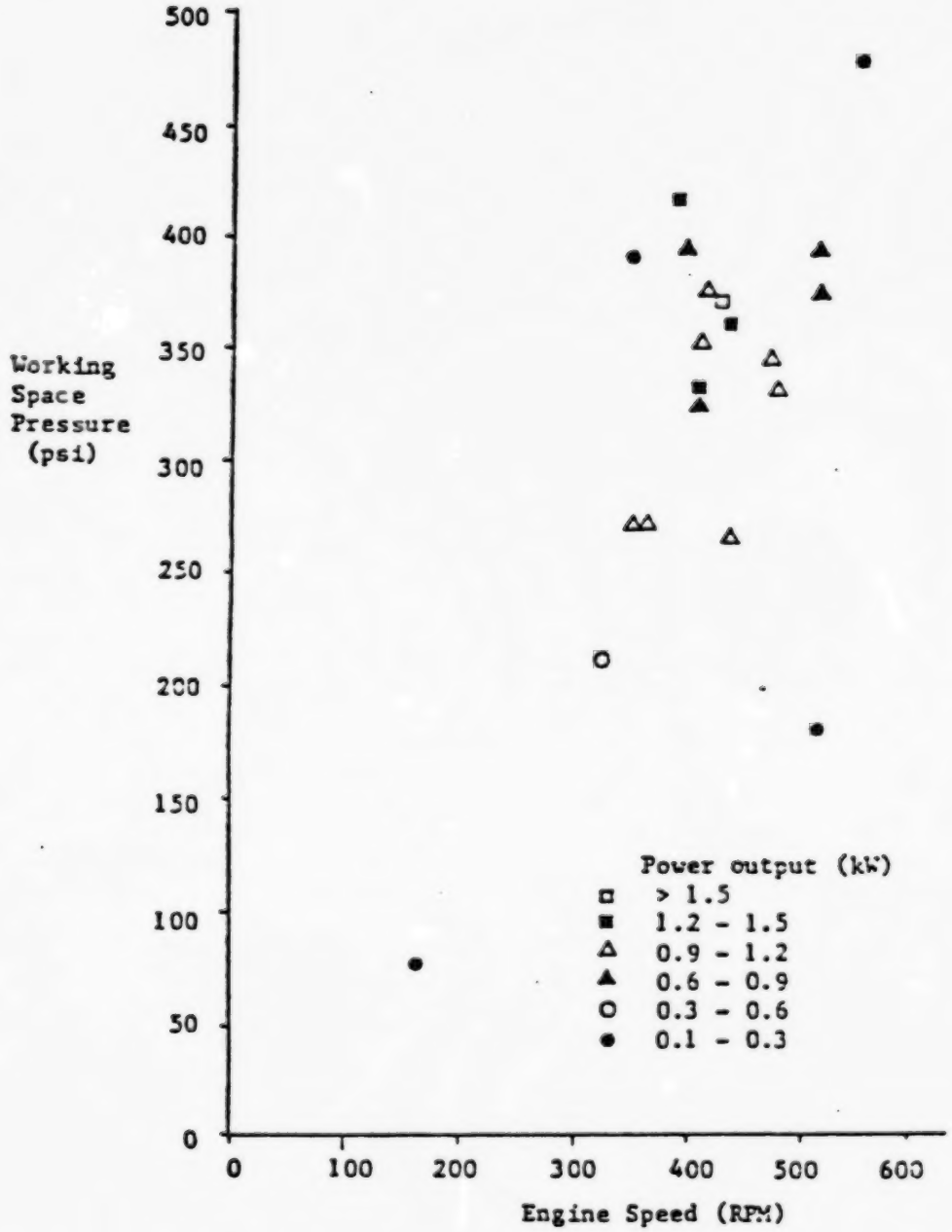

Figure 3 Measured Power Output as a Function of Engine Speed and Mean Pressure

4.0 COMMENTARY AND CONCLUSIONS

This project is one manifestation of the renewed interest in 'alternative energy' sources brought about by gross increases in oil prices in the early 1970's. Coal was recognised as a fuel that is widely abundant throughout the world in politically stable areas. During the decade following the 'energy crisis' substantial effort was invested in systems using coal both directly and indirectly. Direct use of coal in Rankine and Stirling engines was attractive to minimize processing costs. The price to be paid however was the inconvenience of handling coal compared with oil.

It was thought likely that future coal-fired Stirling engines would probably be limited to large units where the difference in the price of coal, and its local availability would justify the inconvenience of its use or the costs of handling equipment. The possibilities for use included stationary power, railway locomotives, marine engines, off-highway vehicles for mining, forestry, construction and agriculture in a power range 0.5 to 5 MW.

Support for this definition of the applications of Stirling engines came with the appreciation that large diesel engines were slow running with low power ratings in terms of output per unit piston displacement. Whereas automotive diesel engines have a power density in the range 35 to 50 kW/litre (50-70 brake horsepower per litre) engine displacement, larger engines (greater than 1000 kW) (1500 horsepower) have power densities very much less, in the range 15 kW/litre (20 brake horsepower per litre) piston displacement and operate at low speeds, 16 Hz (1000 revolutions per min). Large marine diesels, direct-coupled to the propeller shaft and operating at 1.6 Hz (100 revolutions per minute) have power densities of 1.5 kW/litre (2.0 brake horsepower per litre) piston displacement.

From earlier work on Stirling engines it was known that power densities and engine speeds comparable to the larger diesel engines could be achieved with air as the working fluid.

In the 1950's there was a move away from air to the light gases, helium and hydrogen. This permitted elevation of the speeds and power densities achievable with Stirling engines to the levels achieved with diesel engines in automotive application. This move raised a seal problem that has not been solved despite 30 years of continuous research and development effort by highly competent teams of engineers and scientists. It is simply not possible with existing technology to contain the light gases at high pressures with dynamic seals operating at high frequency with low power losses and with a long operating life.

For large coal-fired Stirling engines a return to the use of air as the working fluid was indicated particularly since the use of light gases offered no advantage at the low speeds and power densities required. The use of air was attractive because it is readily available

all over the world and any leakage from the engine could be readily replenished by a small engine driven compressor. Air is easier to seal than hydrogen or helium and there is no need to have a large compressed gas storage bottle for periodic replenishment.

The problem with air as the working fluid is that leakage of lubricating oil into the working space could result in an explosive mixture of oil and compressed air in the heater tubes or other hot parts of the engine. The resultant explosion, known as 'dieseling' would destroy the engine. A solution to this problem appeared to be the use of water as the lubricant. Lubrication conditions in Stirling engines are much less severe than in diesel engines. The rates of pressure change are orders of magnitude less and no 'top ring' lubrication problem exists in the Stirling engine. The presence of water in the working space would not affect the engine operation. In fact it could be positively beneficial to lubricate seals and piston rings, converting the seals to hydraulic rather than pneumatic further decreasing the already reduced leakage of air compared to light gases. Research on the use of two-phase, two component (air-water) compound working fluids indicated the future possibility of water injection to the engine hot space as a way to boost the power density during vehicle acceleration or other periods requiring maximum vehicle acceleration.

Given the prospect of a shortage of oil it appeared worthwhile to explore the conversion of diesel engines to operate as Stirling engines. There are several ways that diesel engines could be converted for the elements of a Stirling engine can be arranged in a surprisingly wide variety of ways. Some of the variations were explored by Walker (1981a) with particular reference to the MLW Series 251-C 16 cylinder 3000 h.p. Vee diesel engine. Most of the schemes investigated involved the use of two engine cylinders to achieve a single Stirling system, one acting as the power piston cylinder, the other as the hot displacer cylinder. Thus to achieve the same output from the engine it would be necessary to double the power density from the eight power piston cylinders. This did not appear to be feasible. The attractive alternative was to install additional displacer cylinders each coupled to several of the existing 'power piston' cylinders having the appropriate phasing. Superficially it appeared possible to convert the engine and to reinstall it in the locomotive with the additional equipment required and achieve the same engine output as in the original form. To avoid the complication of adding a mechanical drive system for the displacers the principle was adopted of the free displacer/crank controlled piston espoused in the Ossian Ringbom patent of 1907. Small model engines of this type worked well and encouraged the possibility that larger engines of the type could be made.

All the early work on this concept assumed the use of the diesel engine piston as the power piston of the Ringbom-Stirling. This required piston seals capable of absorbing the entire pressure difference of the working space to crankcase (atmospheric) pressure. It was simply not feasible to pressurize the existing diesel engine crankcase to any significant degree.

Analysis of this arrangement quickly showed very high loads on the

running gear would give rise to unacceptable friction losses and that satisfactory lubrication with water was probably not possible.

To alleviate this problem a power piston/piston rod could be added to the diesel piston with the space below the power piston sealed and pressurized to the minimum cycle pressure, the concept of the 'pressure-balanced piston'. This is the arrangement shown in Figure 2. The concept could be extended further by using the space below the piston as the compression space of a second Stirling engine system operating 180° out of phase to the system above the piston. Moreover with a separate power piston it would be possible to increase the diameter of the new power piston to more nearly approach the large bore/small stroke characteristic favoured for Stirling engines to minimize the thermal losses.

Slow speed diesel engines characteristically have a small bore/long stroke characteristic to facilitate fuel spray distribution and combustion. An example is the Lister engine used for the work reported here, the bore was 114.3 mm (4.5 ins), the stroke was 133.25 mm (5.25 ins). This is very different to the bore/stroke ratio of about 3:1 believed to be near-optimum for Stirling engines. The addition of a separate power piston to the long stroke piston of a diesel engine inevitably results in a long thin or tall engine such as that shown in Figure 2. It would of course be possible to arrange the displacer cylinder horizontal but this introduced gravitational complications in displacer operation. One of the basic precepts of free piston engine design is to strive for vertical cylinder arrangements where possible (Walker and Senft (1985)).

One of the unfortunate consequences of adding a power piston to the reference MLW series 251-C diesel engine was that it would almost certainly not fit back into the locomotive engine compartment.

Nevertheless a decision was made to proceed with the proof-of-principle demonstration engine. Moreover, it was decided, arbitrarily, to make the diameter of the added power piston the same as the diesel piston passing up the opportunity for an increase in diameter. In multiple cylinder engines the increase would be limited by the cylinder centreline distances. In a single-cylinder engine the maximum cylinder diameter is limited by stress, balance and lubrication considerations. The effective piston displacement increases as the square of the diameter whereas the hoop stress and the axial thermal conduction loss increase only linearly with the diameter. Thus it is advantageous to increase the cylinder diameter as far as possible to the optimum bore/stroke ratio of about 3:1.

The lengthy period of design, manufacture and assembly of the prototype engine was occupied also with intense intellectual effort on the topic of Ringbom-Stirling engines, the Lister diesel conversion in particular and more generally on the whole field of large coal-burning Stirling engines.

One important product of this intellectual effort was the development of the Senft Theory for Ringbom-Stirling engine operation, (Senft

(1981)). For the first time it was possible with this theory to predict the motion of the free-displacer and, very importantly, to define the limiting frequency of the 'over-driven' mode of operation during which the engine converted from, onomatopoeically, a 'bang-bang' engine to one with harmonic displacer motion, thought to be the maximum operating frequency of the Ringbom-Stirling engine.

A digital simulation program for Ringbom-Stirling engines was developed shortly thereafter (Srinivasan (1982)) and provided the possibility for parametric exploration of the significant engine design parameters. Much further work remains to be done in this field but an important result obtained was an appreciation of the importance of the mass of the displacer in the dynamics of Ringbom-Stirling engines. Redesign of the prototype engine displacer in an effort to reduce the mass so as to achieve an arbitrary power density target of 17 brake horsepower per litre displacement resulted in a structurally inadequate element.

A notable consequence of this particular aspect of the programme was the conception of novel and superior displacer configurations (Walker *et al* (1983)).

Practical difficulties were encountered in starting and controlling the engine. With the small prototype engine coupled to an electro-dynamometer starting was relatively easy using the dynamometer to provide power. However the problems encountered focussed attention on the question of starting large engines already pressurized to operating levels. Speed control achieved by varying the stiffness of the gas springs appeared, with test-bed experience, much less attractive than at the design stage. Therefore an early concept, due to William Martini, (Walker (1980)) for an independently-driven displacer was combined with the concept for a Ringbom free displacer to a new form of engine, a Martini-Ringbom-Stirling or Fauvel-Stirling. In this arrangement the displacer is independently driven by a small, variable speed, direct current motor. Oscillation of the displacer causes pressure perturbations in the system acting on the piston, moving it in the cylinder and so starting the engine. The power necessary to drive the displacer is quite small since there is no pressure difference across the two faces apart from the pressure drop in the heat exchangers.

Engine speed can be increased by driving the displacer faster and, of course, the displacer driving power requirement increases with speed as a function of the square of the speed. The relatively high displacer driving power can be provided to an increasing degree as the speed increases by a Ringbom-style spring piston and large diameter displacer rod. Pressurizing the spring space causes the displacer to be driven more by Ringbom free-displacer action than by Martini driven displacer action. Energy to drive the displacer comes of course from the heat input to the engine at high temperature.

A simple power equation for Stirling engines devised by William Beale (Walker (1980)) is:

$$P = 0.015 \bar{p} V f$$

where

P = power output (watts)
$\bar{p}$ = mean cycle pressure (bar)
V = power piston displacement (cm^3)
f = frequency (Hz).

The power piston displacement, V, is clearly an important constituent of the power equation. In traditional designs of Stirling engines it is surprising how little of the actual engine envelope is given over to piston displacement, far less than is devoted to the kinematic drive mechanism, the running gear, or the hollow displacer dome and the combustion space.

In a new departure E.R. Bingham devised a form of engine with very large pistons. The engine crankshaft passes through the centre of pistons along the transverse axis and is attached to the pistons by a modification of the well known Scotch-yoke mechanism. The piston displacement of this type of engine is now very large so that the pressure level or the engine speed can be correspondingly reduced in accordance with the Beale power equation given above.

One conceptual design combines Bingham-pistons, a hollow Kentfield displacer and a Fauvel displacer drive. This engine was described by Walker *et al* (1984) and is under active investigation at the present time. Another form of engine incorporating Bingham pistons is a four cylinder engine of the Siemens-Stirling arrangement in which the cold space of one cylinder is coupled through a cooler, regenerator and heater to the hot space of an adjacent cylinder. In this way the number of reciprocating elements per Stirling engine system can be reduced from two to one. The number of cylinders can range from 3 to 6. This type of engine is also the subject of active investigation at the present time.

Little or no work has been done on the coal combustor and thermal transport system for large coal-fired Stirling engines.

One attractive possibility is to combine a fluidized bed coal combustor with a sodium heat pipe thermal transport system. The fluidized bed coal combustor with a limestone feed can use 'dirty' coal with a high sulphur content with little or no harmful emissions. It operates at a temperature of 800°C or thereabouts and extraordinarily high rates of heat transfer can be achieved.

Use of a sodium heat pipe to transport thermal energy from the fluidized bed to the Stirling engine is advantageous from a number of aspects. First it permits great flexibility in the geometry of the fluidized bed/engine arrangement. Sodium heat pipes up to 5 m in length have been demonstrated with only minor heat losses and decrease in temperature along the length. Use of a heat pipe permits transmission flux densitities that are orders of magnitude greater than can be achieved by simple thermal conduction using the purest copper or silver conductors.

The thermal fluxes achieved in evaporation and condensation of the sodium are very high. The high condensing heat flux permits the heater tubes of the engine to be reduced in diameter and length. This reduces the internal void volume, the dead space of the engine and in consequence increases the power output of the engine. There are no hot spots on the heater tubes because the temperature of the condensing sodium is the same all over the head. Thus the *mean* temperature of the heater tubes become also the *maximum* temperature and may be increased to a prudent fraction of the metallurgical limit with beneficial effect on both the efficiency and power output of the engine.

A two stage heat pipe would likely be used in practice. Multiple first stage heat pipes would convey heat from the bed to an intermediate interface where condensing sodium in the first stages would evaporate sodium in a single second stage system. Separate first stage heat pipes would permit punctures or leaks of sodium caused by the aggressive, hostile environment of the fluidized bed to be tolerated,while maintaining operations, albeit at a reduced level.

A gas ballasted heat pipe for the second stage would provide the mechanism for automatic control of the temperature level and a safety 'thermal dump' in the event of unscheduled engine shutdown or seizure. Various aspects of sodium heat pipe application to Stirling engines including the design of a test unit for the prototype proof-of-principle engine design were given by Walker (1983).

The alternative method of coal-firing a Stirling engine is by a chain grate stoker and direct radiant and convective heat transfer. A molten aluminum bath may also be provided here to act as an intermediate thermal flux transformer accepting a low flux/high area input to the bath and providing a high flux, minimum area constant temperature feed to the engine heater.

The recent successful development and operation of six coal-fired ore-carrying ships for Australian coastal service with unmanned machinery compartment encourages the belief that, at least for large engines, there are little or no technical impediments to the direct use of coal as a fuel.

Economic adjustments and improved conservation measures in the decade following the energy crisis have eased the urgency of the situation to the extent that there is presently an 'oil glut'. This is expected to be a temporary phenomenon. In the longer term the future use of coal as a major fuel remains highly probable and it is certain that large coal-fired Stirling engines will find increasing application as power systems in a variety of applications.

China is well endowed with coal resources and to a lesser extent with oil. Strenuous efforts are being made by the Government of China to carry out the industrialization of China on a coal-burning rather

than an oil-burning base. To this end several major research/development engineering groups have been established at the Shanghai Marine Diesel Engine Research Institute, the Institute for Engineering Thermophysics, Beijing and the Institute for Water Transportation, Wuhan. The development of large coal-fired Stirling engines is expected to result from these substantial Chinese efforts.

Major programmes on Stirling engine developments are in progress elsewhere. Many groups and organizations are actively concerned with Stirling engine developments in Japan. Other long-term activities are in progress in Sweden, Germany, Holland, Gt. Britain, Italy and France. Major work is being done in the USSR. Minor programmes are in progress in the United States.

5.0 REFERENCES

Senft, J., (1981a), Parameter Effects in Hybrid Stirling Engines, Consultant Report, University of Calgary, Department of Mechanical Engineering.

Senft, J., (1981b), The Hybrid Stirling Engine, Proc. 16th Inter. Soc. Energy Conversion Eng. Conf., Atlanta, Ga., August.

Senft, J., (1983), First Order Analysis of Ringbom-Stirling Engines, Proc. 18th Inter. Soc. Energy Conversion Eng. Conf., Orlando, Fla.

Walker, G., (1973), Stirling Cycle Machines, Oxford University Press, Oxford.

Walker, G., (1980), Stirling Engines, Oxford University Press, Oxford, 550 pp.

Walker, G., (1981a), The Stirling Engine for Railway Locomotive Application, Report No. TP2930E, Transport Canada, Transportation Development Centre, Montreal, Quebec.

Walker, G., (1981b), Phase 1 Design Report, Ringbom-Stirling Engine, Transport Canada, Transportation Development Centre, Montreal, Quebec.

Walker, G., Fauvel, R., Srinivasan, V., Gustafson, R., van Benthem, J., (1982), Future Coal-Burning Stirling Engines, Proc. I. Mech. Eng., Vol. 197, No. 46, London (reprinted from Proceedings of the Conference: Stirling Engines, Progress to Reality, Inst. of Mech. Eng., London, held at the University of Reading, U.K., March/April 1982).

Walker, G., (1983), Sodium Heat Pipe Design for Stirling Engines, Report No. TP4843E, Transport Canada, Transportation Development Centre, Montreal, Quebec.

Walker, G. and Senft, J., (1985), Free-piston Stirling Engines, Springer-Verlag, Berlin, Federal Republic of Germany.